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(6) MOLDING OF POLYPROPYLENE FILM ARMOR FOR RADAR ANTENNA HARDENING APPLICATIONS

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FINAL REPORT - May 1977/September 1980 Contract (15) DAAB07-77-C-0476
ETD/SOTAS Procurement Branch
FMCO, USAERADCOM
Ft. Monmouth, N.J. 07703

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Watertown, Massachusetts 02172

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ABSTRACT

The general objective of this project was to establish a production capability for rigid armor panels molded from cross-plied, unidirectionally oriented polypropylene film. Armor of this type has applicability as a radome material. The purpose of establishing this production capability is to provide for the contingency of meeting estimated military needs for a period of two years after completion of the contract and, to establish a base and plans which may be used to meet expanded requirements.

To fulfill the stated objective it was necessary to complete the following tasks:

Engineering Sample Phase:

- o Design and proof tooling,
- o Verify processes which were furnished at the beginning of the project, and
- o Preliminary testing;

Confirmatory Sample Phase:

- o Fabrication of sufficient samples using the established process for more comprehensive testing, and
- o Testing of samples, and

Demonstration Phase:

- o Document process used and equipment required, and
- o Brief interested parties and conduct complete process demonstration.

These tasks were successfully performed and the general objective of this project has been achieved. A production capability for polypropylene armor has been established, and in the process, opportunities for additional process advances have been identified.

UNCLASSIFIED REPORT NO. AMMRC TR80-54

SWEDLOW REPORT NO. ER-915

MANUFACTURING METHODS AND TECHNOLOGY PROJECT TO ESTABLISH PRODUCTION TECHNIQUES TO MANUFACTURE RIGID POLYPROPYLENE ARMOR FOR RADAR ANTENNA HARDENING

FINAL REPORT

FOR PERIOD COVERING

5/31/77 THROUGH 9/15/80

PREPARED BY

MR. GLENN COOK

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12122 WESTERN AVENUE
GARDEN GROVE, CALIFORNIA 92645

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Project Objective

The general objective of this project was to establish a production capability for rigid armor panels molded from cross-plied, unidirectionally oriented polypropylene film. Armor of this type has applicability as a radome material. The purpose of establishing this production capability is to provide for the contingency of meeting estimated military needs for a period of two years after completion of the contract and, to establish a base and plans which may be used to meet expanded requirements.

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FOREWARD

This report covers work performed under contract DAAB07-77-C-0476 for the ETD/SOTAS Procurement Branch, FMCO, USAERADCOM, Ft. Monmouth, N. J. This contract was carried forward under the technical direction of the Army Materials and Mechanics Research Center (AMMRC), Watertown, Massachusetts. Mr. Anthony Alesi was the project director. Film used in this project was uniaxially oriented by AMMRC. The film was then mandrel wound to develop a cross-plied pad arrangement by En-Tec Inc., Salt Lake City, Utah. In addition to acknowledging the valuable assistance and direction provided by Mr. Alesi, it is important to note the significant contributions made by Dr. Joseph Prifti, also of AMMRC. In addition, helpful guidance on electrical testing was provided by Mr. Russell Wagner and Mr. John Borwick of the Electronics Research and Development Command, Fort Monmouth, NJ. Among the Swedlow, Inc. staff which made indispensable contributions toward the success of this project are; R. Doerr, C. Gibson, J. Peterson, R. Back, C. Bailey, M. Winstead, and T. Scarpetta.

As a result of work performed under this contract, the process for manufacturing polypropylene armor has become production ready and the suitability of such armor, derived from the production process, for radar antenna hardening has been verified.

This project has been accomplished as part of the U.S. Army Manufacturing Method and Technology Program, which has as its objective the timely establishment of manufacturing processes, techniques or equipment to insure the efficient production of current or future defense program needs.

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UNCLASSIFIED TITLE

MOLDING OF POLYPROPYLENE FILM ARMOR FOR RADAR ANTENNA HARDENING APPLIC

ABSTRACT

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POLYPROPYLENE FILM ARMOR

(J)

INTRODUCTION

Polypropylene (PP) film armor consists of multiple plies of highly unidirectionally oriented film. An assembly of such cross-plied films possesses exceptional resistance to penetration by munition fragments. This capability is essentially retained when the assembly is molded into a rigid sheet by heat and pressure. The film starts out as a blown tube extruded from polypropylene homopolymer. The collapsed tube is subsequently stretched uniaxially in an oven equipped with radiant heaters. The resulting oriented film is much reduced in width and has a double layer thickness of about 1.5 mils. Winding on a mandrel at $\pm$ 45 degrees is then performed and the product cut off the mandrel when an appropriate quantity of film has been wound. This procedure accomplishes cross-plying and assembly into pads. Pads can be stacked to achieve desired armor weight and cut to the desired size and shape. The flexible pads can be used as armor as is (surface protective covers and stitching to reduce bulk can be useful) or can be further processed into rigid sheets by molding.

The Phillips Scientific Corporation in the period 1968-74 under contract to the Army Materials and Mechanics Research Center (AMMRC) in Watertown, Massachusetts investigated the film stretching and sheet molding processes and also the making of transparent rigid sheet. AMMRC during this period and continuing up to the present conducted its own in-house research and development on these processes. Swedlow, Inc. was charged in the contract being reported with establishing the processes, techniques and equipment for manufacturing rigid armor sheets of a quality suitable for hardening radar antennas against high explosive munition fragments. The Electronics Research and Development Command, Fort Monmouth, NJ had in 1975 determined the electrical characteristics of rigid armor panels and concluded that these had applicability for such hardening without serious degradation of radar performance.

The general objective of this project, therefore, was to establish a production capability for rigid armor panels molded from cross-plied, unidirectionally oriented polypropylene film. The purpose of establishing this production capability is to provide for the contingency of meeting estimated military needs for a period of two years after completion of the contract and, to establish a base and plans which may be used to meet expanded requirements.

The key tasks of this manufacturing technology demonstration project were intended to deal with: process scale-up; placement of the process in a manufacturing environment; then, the manufacture of representative panels; followed by, testing to assure a reproducible product yield and; finally, a demonstration of the manufacturing to interested parties from industry and government. These tasks were somewhat altered, however, as the process scale-up demanded considerably more time and money than anticipated. In line with the nature of a "Manufacturing Methods" project the subject program was intended to concentrate on incorporating the previously developed process into an efficient, demonstrable production scheme. With the problems encountered in the initial phase of the project (Engineering Samples generation) the task emphasis was shifted as shown below.

Task	Budget Percentage Original	Budget Percentage Final
Engineering Samples	36%	75%
Confirmatory Samples	28%	25%
Pilot Run	36%	Cancelled
Production Capability Demonstration	Negl.	Negl.

At the start of work, oriented film was obtained from a company that produced oriented ribbon from polypropylene film. This company had worked with AMMRC in developing its procedures and equipment to produce suitable film. However, the film supplied split so easily in the machine direction that it was not considered suitable for mandrel winding. Also it had been drawn to a lesser extent than optimum. It was decided to use film that would be supplied and oriented by AMMRC on its equipment. The contract work was delayed until mandrel wound film pads were delivered. Upon receipt of this new material, numerous process trials were made while attempting to achieve technically acceptable panels. Ultimately, acceptable panels were produced in a repetitive fashion, such that confidence in the process was established, with the causes of problems which had been encountered, satisfactorily explained.

As a final step in the project a manufacturing demonstration was presented to interested parties from industry and government, thus, the successful completion of the project was illustrated.

The technical qualities required of the panel include,

- o Radar transparency
  - Limited voids and inclusions
  - Minimum visual degradations which could indicate an effect on radar transmission
  - Thickness control
  - Flatness
  - Dielectric constant control

- Minimum fusion bonding strength between film plies consistant with structural requirements in order to maximize ballistic resistance.

- Surface protection from the environment and achievement of camouflaging.

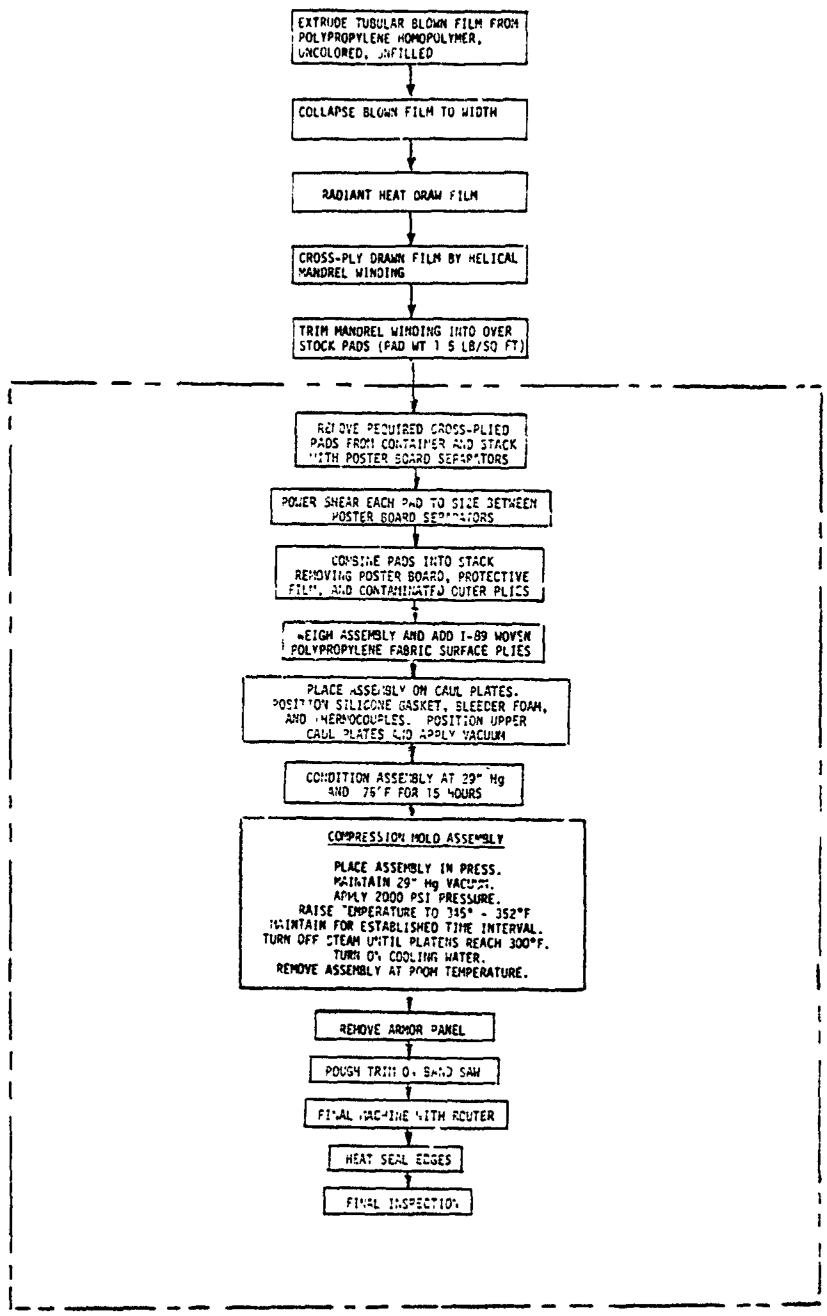
- Retention of film mechanical properties.

It may be noted that the primary tasks previously outlined were supplemented by tasks involving incorporation of surface treatments to protect the panels from the environment, surface camouflaging, edge sealing, the establishment of dimensional controls and, the verification of suitable functionality.

These tasks, outcomes, resulting process, conclusions and recommendations are presented in the remainder of this report. It is worth noting at this point, however, that simultaneous to the execution of this project and under separate contracts, Swedlow executed a Manufacturing Technology project directed toward transparent polypropylene armor production (also for AMMRC) and developed the process for manufacturing compound curved polyolefin armor in, thus far, thicknesses up to 4 inches. Additionally, new applications for this unique armor continue to emerge. As a result of the work performed under this contract a production capability has been established which provides the opportunity to improve the survivability of the men and machines of the U. S. defense system.

PROCESS DESCRIPTION

The general process used for fabricating the polypropylene armor panels is shown below. The steps enclosed in phantom lines were those addressed in the subject contract and dealt primarily with the fusion bonding of the polypropylene films.



Before discussing the details of the process it is appropriate to describe the process theory. This will give insight into the general problems associated with polypropylene armor production and will allow analysis of the solutions to these problems. Additionally, this discussion of theory will provide a basis for the discussions which are to follow concerning necessary process variations from the original process plan and those recommendations which are finally presented.

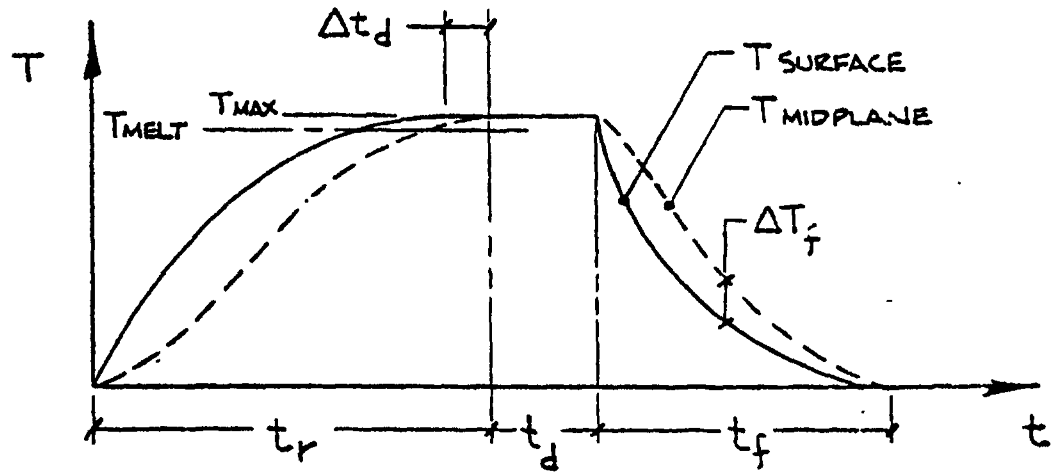
The theory of fusion bonding considers the application of heat to a material sufficient to melt (soften) either a small fraction or a majority of the material cross-section and, through the application of pressure, two or more such elements are fused together. In the case of the subject polypropylene films which are to be fused, it is necessary to melt only a small fraction of the film material and develop only superficial fusing of the individual plies in order to preserve the ballistic properties of the film in its original state. It has been demonstrated that if the films are highly fused (i.e., highly melted during fusion) the ballistic properties are significantly reduced. Polypropylene melting (or more correctly softening) is restricted by the interaction of three key material properties; 1) molecular weight distribution, 2) degree of crystallinity and, 3) tacticity. The low molecular weight components will be the first to melt. In this case however, low molecular weight material is not significantly present. The non-crystalline, or amorphous, portion within the material has a lower melting temperature than that of the highly crystalline structure, and will therefore begin to melt or soften first. The polypropylene films used in the subject program are received with a high degree of crystallinity. The tacticity, then, will be most significant in its effect on the polypropylene melting in that the syndiotactic form has a reported $T_m = 138°C$ whereas the isotactic form is much higher at $T_m = 186°C$. The conditions under which propylene monomer is polymerized controls the tacticity. At melting temperature the degree of crystallinity is gradually reduced with an amorphous viscoelastic structure resulting when the film is fully melted. Melting is a rate controlled process, and as such, with the right amount of energy input and proper temperature control the material is prepared for correct bonding. Pressure is applied to the heated material to cause the melted components of adjacent plies to be placed in very close proximity to facilitate bonding through polymeric chain entanglement. As the pressure increases, given a specific melt fraction, bonding is improved until effective entanglement is achieved, at which point further improvements in bonding would not be expected. To gain the surface proximities necessary for good fusion it is necessary to exclude contaminates such as film lubricants, oils from film handling and air between plies. Thus, in summary, material related properties affecting controlled fusion bonding include,

- o Molecular weight distribution
- o Degree of crystallinity
- o Tacticity

  &

- o Contaminants (both internal and inter-surface)

The temperature and pressure control discussed, necessary for the critical fusion bonding, is applied in the following cycle:



<u>Symbols:</u>

T = Temperature

t = Time

Subscripts:

r = rise

d = dwell

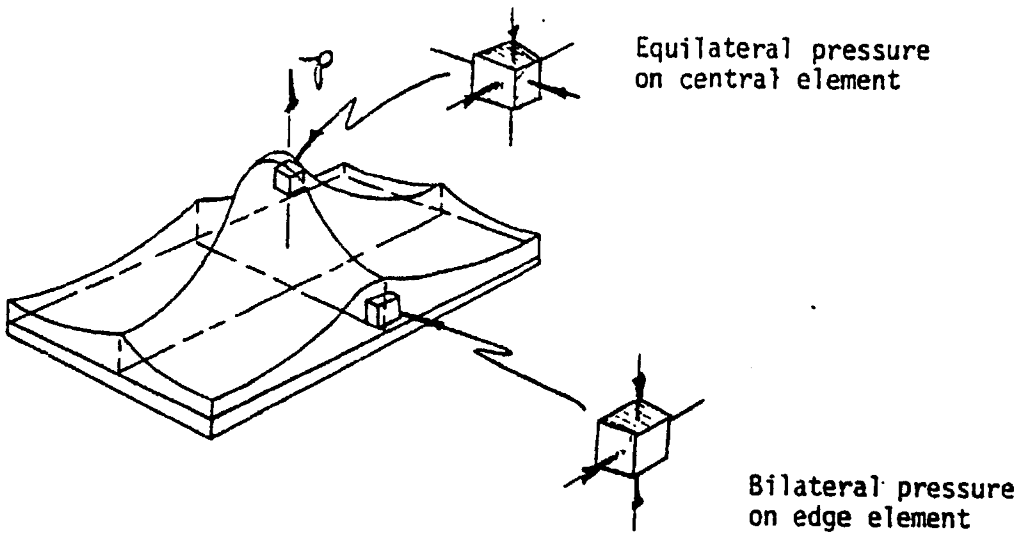
f = fall

<u>Notes:</u>

1) Constant pressure is applied for the complete cycle

2) Δt_d represents the inaccuracy in judging the start of thermal dwell based on the temperature difference between panel surface and mid-plane.

In addition to these general fusion bonding process features, the mold configuration and, specifically, the surface plate quality is quite important. These features control the flow of material and pressure distributions developed within the panel during fusion bonding. It is believed that the actual pressure distribution developed is similar to that shown below and is due to edge related flow and a restricted flow in the planform central region. This pressure distribution model is thought to be panel size dependent.



The process which was furnished to this project dealt with most of these variables, with the exception of the quality of the mold surface plate. The lack of appreciation for the influence of this characteristic on the bonding of surface and near-surface plies caused time delays and changes in the initial project plan while solutions were being developed.

The final process arrived at in this project is described in the following "Manufacturing Outline":

FINAL

MANUFACTURING OUTLINE - PP ARMOR PRODUCTION

STEP 1 MATERIAL CHARGE WEIGHT CALCULATION

Determine desired sheet size and thickness.

Calculate charge weight based on theoretical Sp. Gr. of Polypropylene (.91 gm/cc) plus 3.2% flow factor.

Example:

To mold a sheet 1.160 ± .015 thick in a mold with a vacuum frame which has inside dimensions of 26" x 36". Allow 3/4" all around sheet to place vacuum bleeder material (ZAP[1] foam). Preform size will be 24 1/2 x 34 1/2.

Calculation:

24.5" x 34.5" x 1.160" (Desired panel thickness) x 16.4 cc/in^3 x .91 gm/cc (sp. Gr. of Polypropylene) x 1.032 (for 3.2% flow) = 15,100 gms.

Determine number of cross plied oriented polypropylene pads required for each panel. Example calculation with the AMMRC supplied material at 1.25#/ft^2. (567 gm/ft^2)

Calculation:

$$\frac{\text{Desired wt of XP mat'l. (gms)}}{\text{Area of panel } (ft^2)} \times \frac{1}{567\ gm} ft^2 = \text{No. of pads}$$

$$\frac{15{,}100}{\frac{24.5 \times 34.5}{144}} \times \frac{1}{567} = 4.54 \text{ pads} \therefore \text{ use 5 pads}$$

STEP 2 MATERIAL PREPARATION

Put on thin white cotton gloves for the following operations. Place each PP pad on a piece of .050 inch thick white poster board. Place a sheet of poster board on top and trim the layup to size on the power shear. Position all the layups on one stack and then re-stack while removing the polyethylene film and the separator boards. This is done as follows:

A. Remove top board and position next to layup stack.

Remove polyethylene film and any layers of oriented polypropylene which exhibit contamination.

Replace top board and grasping edges of top and bottom board from one pad, flip over and position beside layup stack.

(Ref. 1) An open cell foam material. Available as No. 10-PPI from Wilshire Foam, 1240 E. 230th St., Carson, CA. 90745.

Remove the present top board.

Remove the polyethylene film and any layers of oriented polypropylene which exhibit contamination.

Replace the top board.

B. Repeat the above sequence with the second pad.

Place on top of the first pad.

C. Carefully remove the two middle cardboard plies by uniformly pulling them out in opposing directions at the same time.

D. Repeat steps B and C with each pad until the entire layup stack is complete.

STEP 3 WEIGHING LAYUP

Wear white cotton gloves.

Place a clean carrier plate (1/4" plywood) and top ply of poster board on a scale and tare to zero.

Place two plies I89[2] fabric (cut 1/4" oversized and washed with methanol) over the assembly, replace the posterboard, then carefully invert the entire assembly onto the scale.

Remove the top poster board and carefully skin back layers of the oriented polypropylene until desired weight is obtained. (Desired weight equals calculated weight less the weight of two plies of I89).

Position two plies of cleaned I89 on top of the assembly.

Place carrier plate next to the mold caul plate and slide the layup into position by grasping the bottom ply of surfacing fabric.

STEP 4 EVACUATING ASSEMBLY

Place silicone gasket ring on caul plate.

Place two ply of 1/2" x 3" ZAP foam between layup and gasket.

Position thermocouples through the vacuum line into the layup.

Place top caul assembly over the layup and clamp in place until the gasket is slightly compressed.

Pull vacuum to 29 in. Hg.

Place thermocouples in caul plate receptacles and label each.

Place the assembly in an oven at 175°F for 15 hours.

(Ref. 2) A woven U-V stablized polypropylene fabric, olive color. Supplier: AMOCO Fabrics Co., 550 Interstate North, Atlanta, GA. 30339

STEP 5 MOLDING PANEL

Turn off vacuum pump and transport assembly to the press. Be sure vacuum valve is closed to maintain vacuum on the assembly.

Turn on vacuum pump and steam and close press to 2000 psi on the laminate.

Connect thermocouple leads to potentiometer.

Record all data on Molding Record every 5 minutes.

Start cycle time when platen surfaces reach 335°F.

Maintain platen temperatures at 348°F to 352°F during heat on cycle.

For one inch nominal panel maintain steam on for a maximum of 90 minutes (25 minutes for 3/8" thickness).

Turn off steam and open bypass.

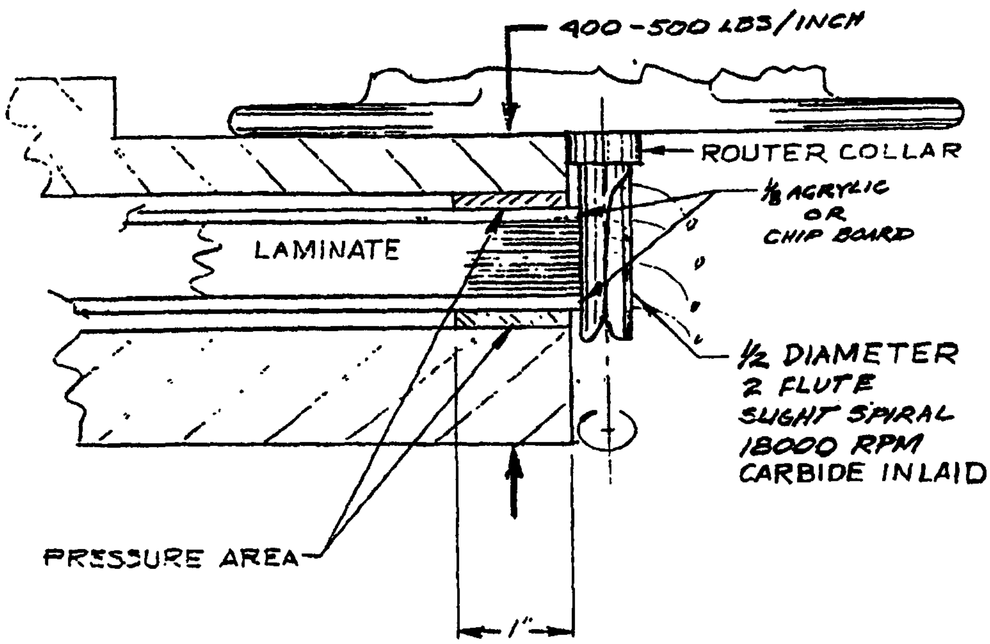
Turn on cooling water at 300°F midpoint temperature.

Remove panel at room temperature with maximum allowable temperature differential of 20°F from panel surface to midpoint.

STEP 6 MACHINING PANEL

Trim on band saw 1/8" to 3/16" oversize all around.

Clamp on milling machine table with 1/8" thick acrylic (or other non-metallic rigid material) on top and bottom along trim edge as shown below. Sheets may be stacked and routed together to reduce unit time.



Route edge with 1/2" diameter - 2 flute carbide router at 18,000 RPM to final dimensions.

ALTERNATE MACHINING METHOD

Clamp untrimmed panels on milling machine table with 1/8" thick acrylic (or other non-metallic rigid material) on top and bottom along trim edge. Sheets may be stacked and cut together to reduce unit time.

Cut edge with a carbide inlay saw blade with 1/4" wide teeth on a 30 inch diameter blade at two teeth per inch.

Blade speed - 238 RPM
Feed speed - 1.42 inch/min.
Coolant - Water soluble Johnson's TL 131[3]

STEP 7 HEAT SEALING EDGES

Clamp trimmed edges with metal bars to prevent relaxation of the oriented film during the fusion operation.

Hold a butane torch flame approximately one inch from the edge of the panel, and move the flame back and forth until the entire edge exhibits a high gloss due to localized melting of the polypropylene. Allow to cool to room temperature before releasing the clamp pressure.

This technique can also be used to seal edge debonded areas and raised edges caused by the cutting operation. To do this, re-clamp the panel with the bars 1/16 inch away from the edge and smooth down the raised edge with a metal spatula as the material melts.

STEP 8 FINAL INSPECTION

End product inspection requirements have been established for polypropylene film Armor panels under AMMRC specification PD-105. These requirements, and related test procedures, are listed below.

Ballistic Requirement

The V_{50} ballistic limit shall not be less than the value specified in Supplement 1 (Classified Confidential) when tested in accordance with MIL-STD-662A. The spacing between impacts shall be at least 4 inches with no impact less than 2 inches from an edge.

(Ref. 3) A water soluble coolant. Available from Pacific Abrasives, 2240 So. Yates Ave., Los Angeles, CA. 90022.

S-Band Frequency Characteristics

The requirements and test procedures are as described in Supplement 2 (Classified Confidential). In addition the panels shall have a dielectric constant of 2.3 or less and a loss factor of 0.0005 or less when tested as follows:

Testing shall be conducted at 73.4 plus or minus 3.6°F and 50 plus or minus 5 percent relative humidity in accordance with ASTM D2520-70, Method A or B. Specimens for testing armor panels (3.2.1.2) shall be either cut to the length and width required but maintaining the panel thickness or shall be molded to the dimensions required following the panel procedures including, except for Style 1, the incorporation of camouflage.

Sizes and Tolerances

Cut and fused edge panels (Finish 2) shall be 24 x 34 inches within a tolerance of plus or minus 0.032 inch. Thickness tolerances for all panels shall be plus or minus 0.015 inch.

Edge Finish

The molded panels shall be cut to size and the edges finished by fusion either as part of the cutting process or as a separate operation subsequent to cutting. The finished edge shall not be split, shall not have a raised lip greater than 0.030 inch in height and shall not be delaminated as evidenced by whitish borders on the sheet faces to an extent greater than 0.060 inch from the edges.

Soundness

The armor panels shall be translucient and may show striations indicative of the mandrel winding pattern. They shall be free of edge splits and voids, unbonded areas and blisters as evidenced by whitish areas.

Dimensional Stability

The armor panels shall be dimensionally stable and shall not split or delaminate when tested in accordance with the following procedure. The maximum acceptable change is 0.04 inch decrease in length and width, and 0.010 inch increase in thickness, and 0.06 inch increase in warpage.

Armor panels shall be measured for length and width along center-lines and for thickness at the center. Any existing warpage shall be determined by moving a straight edge longer than the diagonal of the panel over the concave side and measuring the maximum gap between the bottom of the straight edge and the panel surface. The measured panel shall be subjected to the below designated temperature and humidity cycle in a test chamber. There shall be a two hour transition period between cycle phases and between room conditions and the start and conclusion of the cycle in which to change gradually the chamber conditions. The chamber shall start and end at room temperature and humidity conditions.

Cycle Phase (in order)	Duration, Hours
A	4
B	16
C	4
A	16
B	4
C	16

Phase A: 185 F and 95 percent relative humidity

Phase B: -70F

Phase C: 185F

Upon completion of the cycle, the panels shall be remeasured for length, width and thickness dimensions, for warpage, and shall be examined visually for edge splits and debonded areas as indicated by the appearance of whitish areas or blisters. The change in dimensions and in warpage shall be calculated.

TOOLING AND EQUIPMENT REQUIREMENTS

Manufacture of the PP armor panels involves a series of processing steps through various types of equipment and tools. These requirements are listed in Figure 2. It should be noted that all equipment such as presses, ovens, power shears, and milling machines are standard capital equipment available in many plastic fabrication facilities.

Special tooling requirements include the Mold Die, Mold Support, Caul Plate Assembly, and Gasket Seals. The basic Mold Die Configuration is shown below.

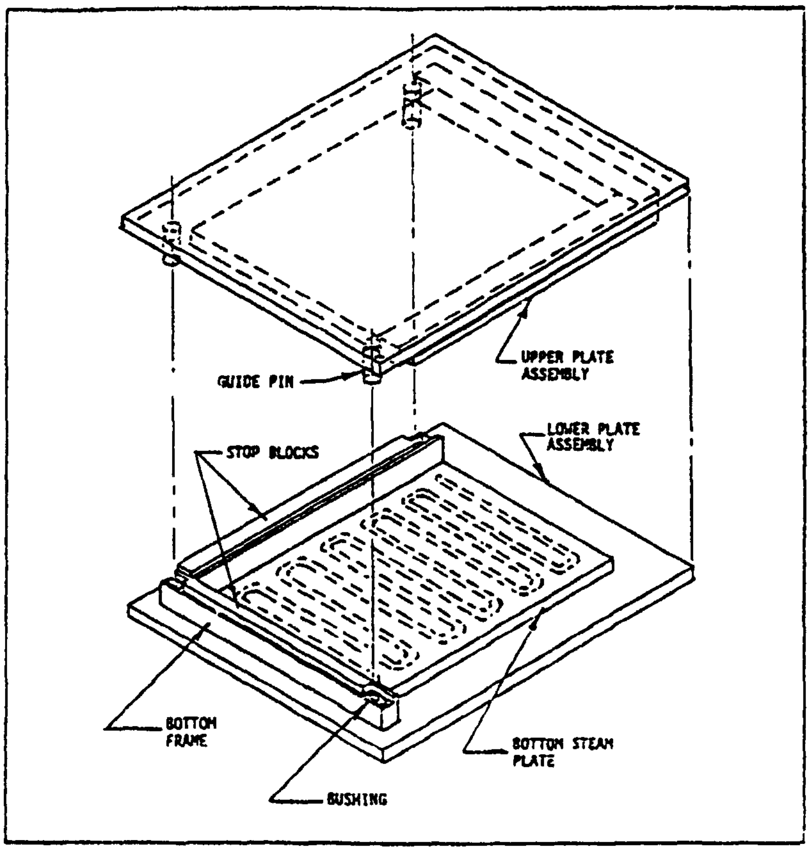


FIGURE 1. MOLD DIE CONFIGURATION

EQUIPMENT & TOOLING LIST

PP ARMOR PRODUCTION

Station	Equipment & Tooling
Material Preparation	Power paper shear. 48" x 60" work table with smooth, non-porous surface. Lightweight cotton gloves. Poster board - .050 inch white 36" x 48".
Weighing Layup	Accurate scale - 20,000 gram capacity. 1/4" plywood carrier board - 26" x 36".
Assemble and Apply Vacuum	Caul Plate Assembly Silicone Gasket Seals Bleeder foam Iron-Constantan thermocouple wire Potentionmeter Cenco vacuum pump Vacuum tubing Shut off valve Transport cart 6 inch "C" clamps (4 req'd)
Condition Assembly	Circulating air oven - 170°F. (To accomodate cart and caul plate assembly) Recording chart drive temperature control.
Molding Panel	Hydraulic Press - steam heated/water cooled platens - pressure to 2000 psi on molding.
Machining	Band saw Milling machine Router
Edge Sealing	Metal topped table Clamp bars (1/2" x 1" x 36") Propane torch

FIGURE 2

The mold die is a matched steel die designed to contain the cross-plied assembly during the lamination cycle. It is a semi-positive compression mold with a steam heating -- water cooling chamber on either side. It has guide pins and busings for alignment and stop blocks for thickness control.

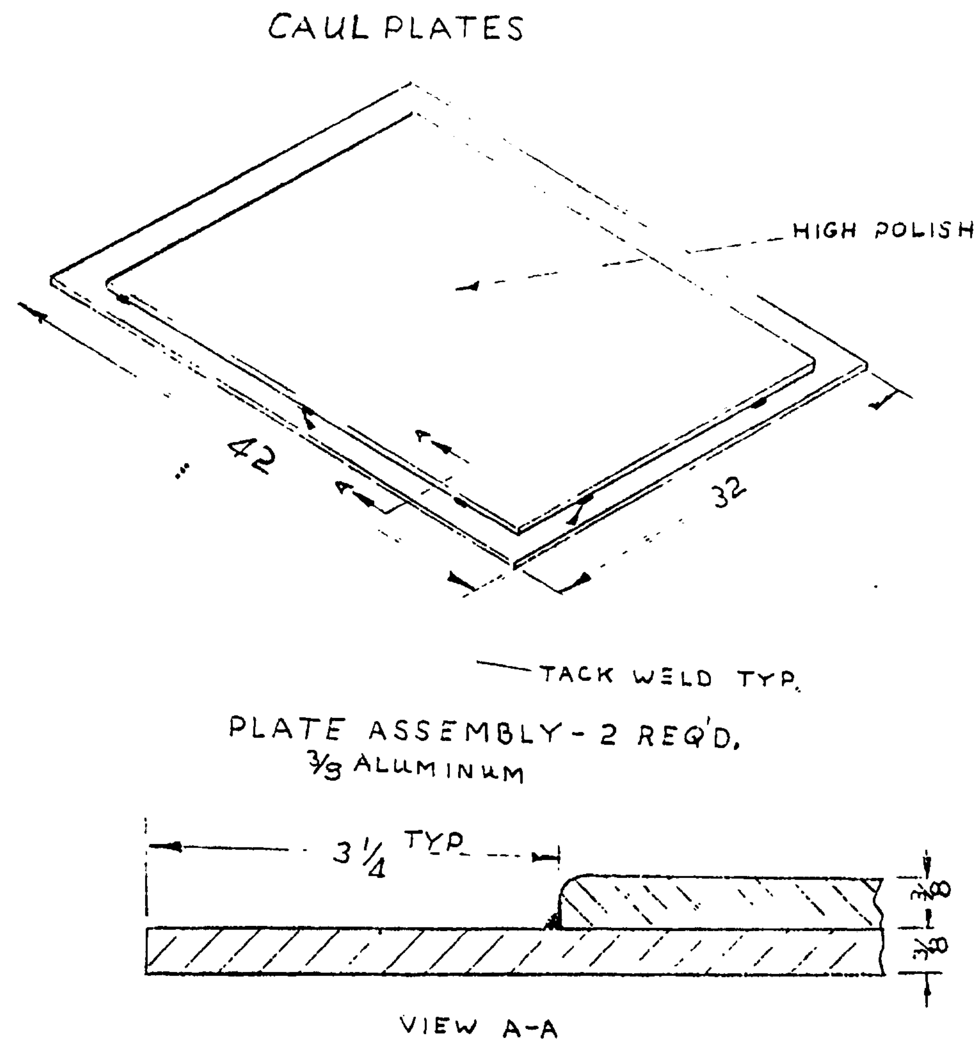
The mold support is a welded I-Beam structure designed to reduce the Taccone press opening to permit installation of the Mold Die and allow complete press closure.

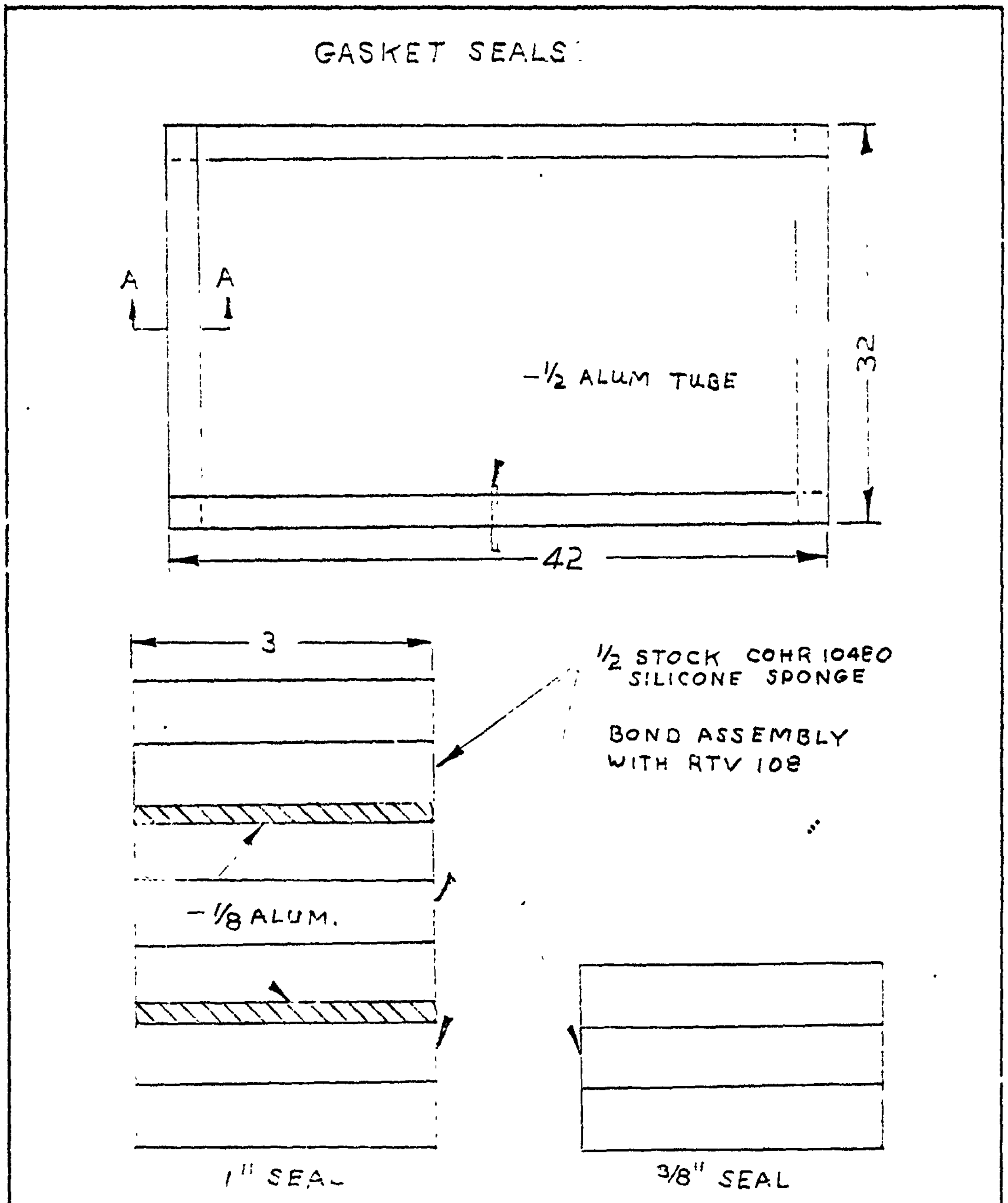
Processing refinements developed during the preliminary investigation phase of the program, required the retention of a vacuum on the film ply assembly throughout the evacuation and fusion phases of the armor panel fabrication. The mold die, as designed, would not provide this capability.

A set of Caul Plates and Gasket Seals were designed to form a system which would permit evacuation of the polypropylene film ply assembly while heating in an oven, then allow the entire layup to be installed in a molding press while retaining a vacuum. The vacuum can then be maintained while heat and pressure are applied to initiate the fusion cycle. The caul plate construction is shown in Figure 3.

The Caul Plate assembly was designed in aluminum to provide excellent heat transfer. The inner plate, which serves as the panel mold surface, is highly polished to provide a smooth armor panel surface and, more importantly, prevent delamination of the panel during the cooling phase of the fusion cycle. The highly polished mold surface allows the fusion bonded armor panel surface to shrink during cooldown independent of the mold surface. This allows the panel to be free of internal stress when the pressure is removed at the completion of the cooldown phase of the fusion cycle. Significant internal stresses could cause delamination of the panel due to the low interply bond strength of this product. The low interply bond strength of the PP armor is required for maximum ballistic efficiency.

The Gasket Seals were designed with a closed cell silicone rubber which combines excellent high temperature resistance with a high compression ratio. These seals are fabricated with 1/2 inch thick strips of foamed silicone rubber bonded with an RTV sealant. An aluminum tube is bonded through each seal to permit attachment of vacuum lines and thermocouple wires. The seal assembly for the 1 inch thick panels is reinforced with 1/8 inch thick aluminum plates to prevent the seal from collapsing during the evacuation phase. The inner caul plate which provides the panel mold surface, also allows a compression space for the seals. The maximum seal compression during the fusion process is 53 percent. This should allow a minimum life of 20 to 30 cycles per seal assembly. The seal construction is shown in Figure 4. The caul plate and gasket seal assembly are depicted at the beginning and conclusion of the fusion cycle in Figure 5 to demonstrate maximum seal compression.


CAUL PLATES
HIGH POLISH
42
32
A
A
TACK WELD TYP.
PLATE ASSEMBLY - 2 REQ'D.
3/8 ALUMINUM
3 1/4 TYP.
3/8
3/8
VIEW A-A
FIGURE 3



VIEW A-A
FIGURE 4

PREPARED BY G.COOK	SWEDLOW Inc.	PAGE NO OF.
CHECKED BY	SEAL COMPRESSION 1" PANEL	REPORT NO.
DATE		CUSTOMER AMMRC

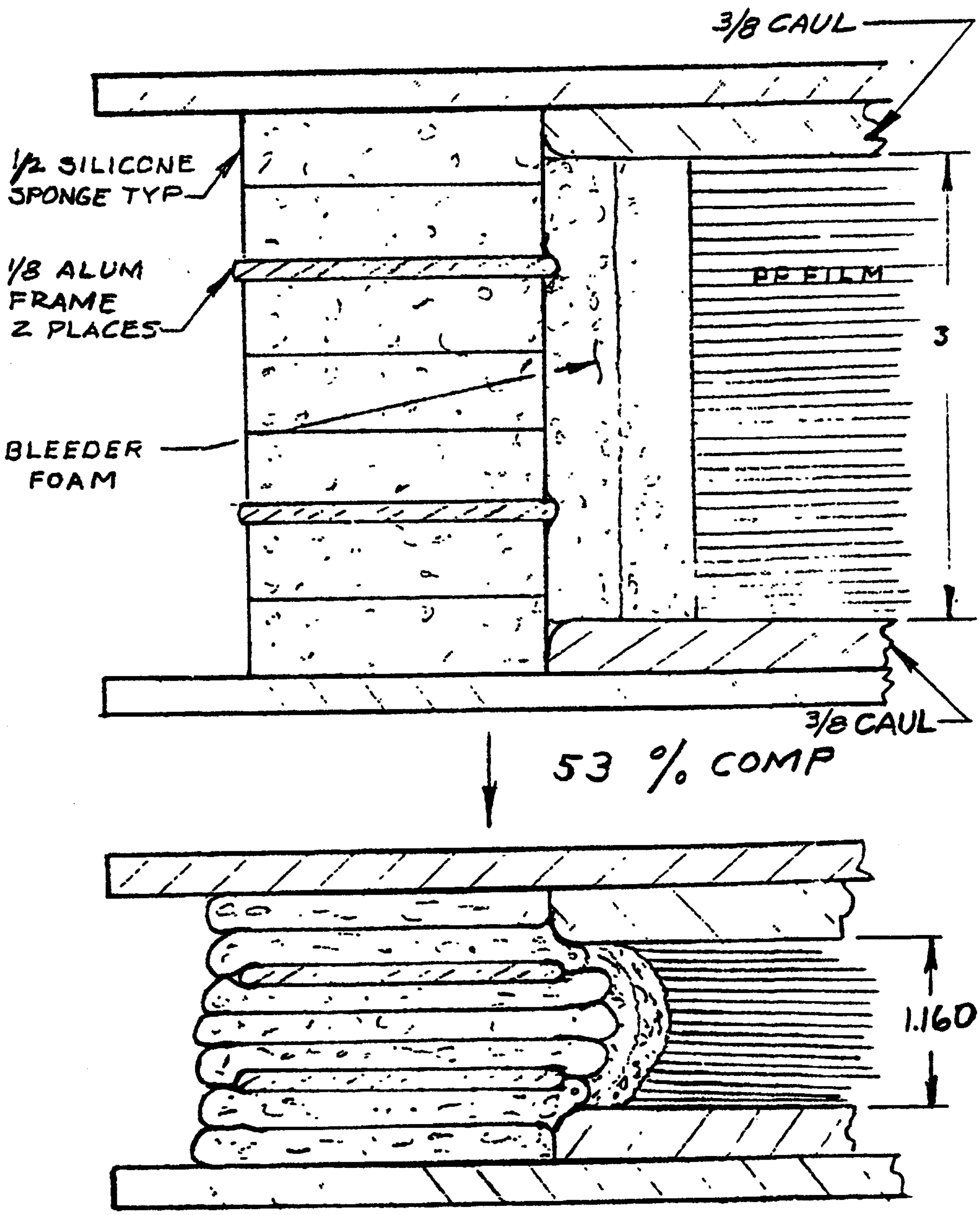
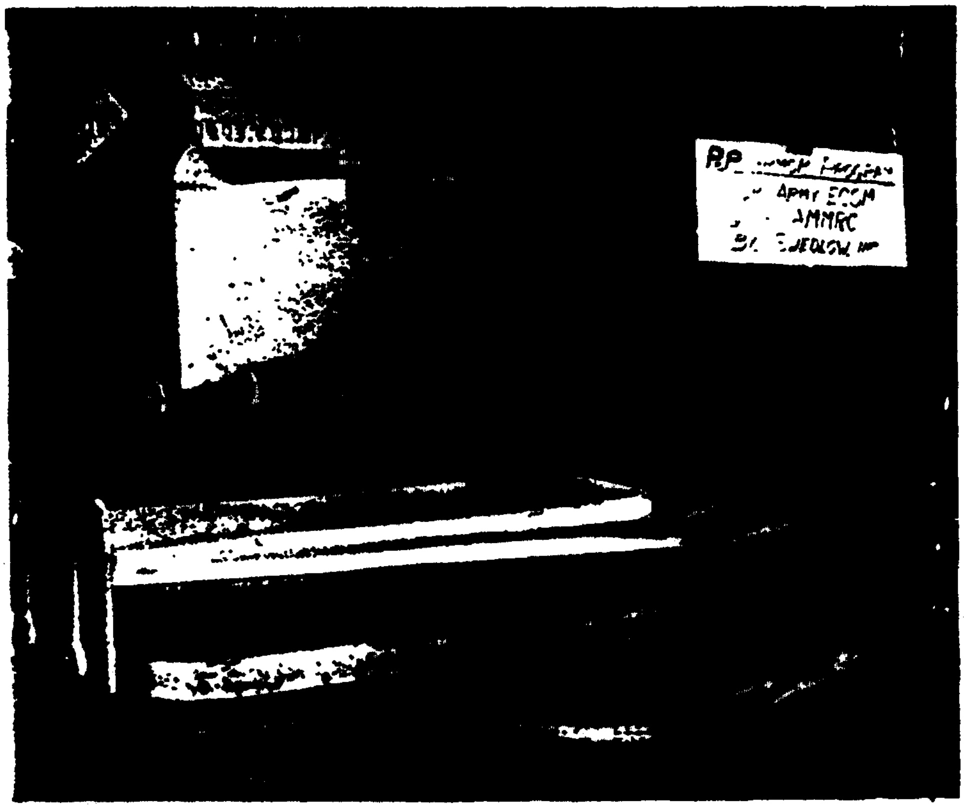


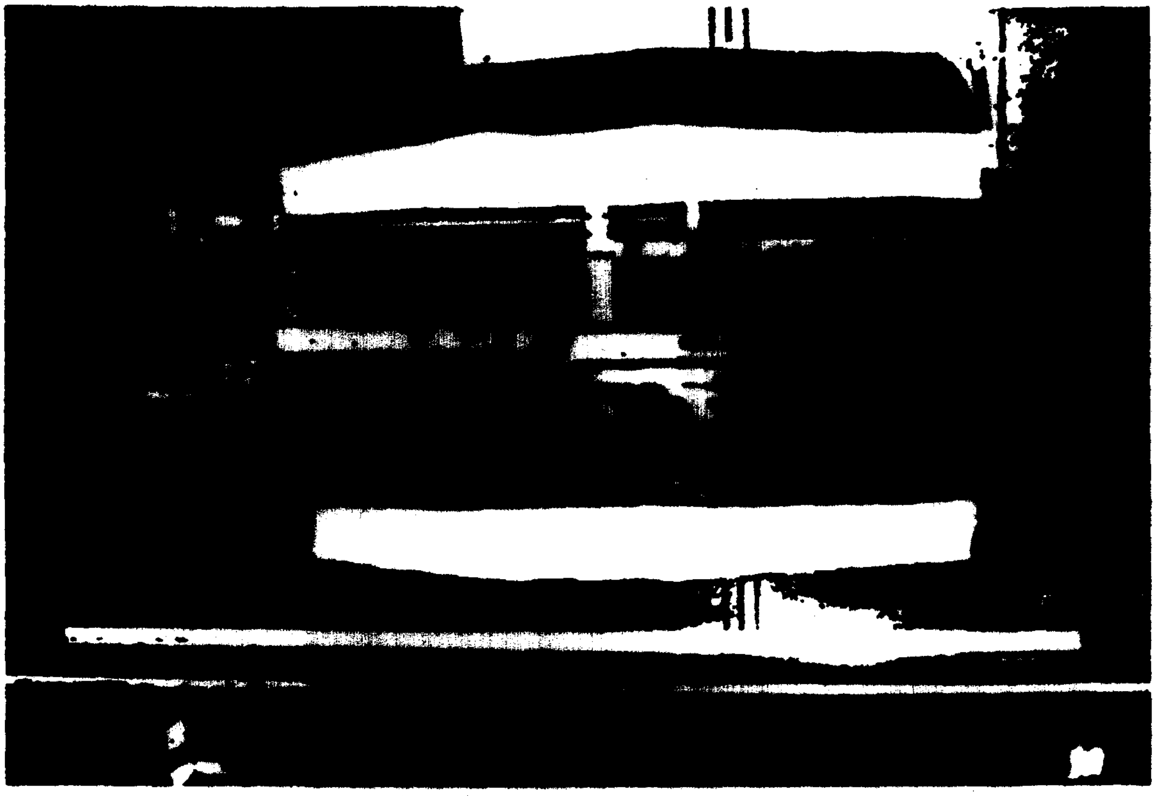
FIGURE 5

The processing refinements, developed during the preliminary investigation phase of the program, dictated the use of the above Caul Plate/Seal Gasket system for the armor panel fabrication, thus the Mold Die was utilized as a set of heating and cooling platens throughout the Engineering and Confirmatory Sample runs. This also resulted in a panel size reduction from the desired 32 x 42 inch size to a final configuration of 24 x 34 inches.

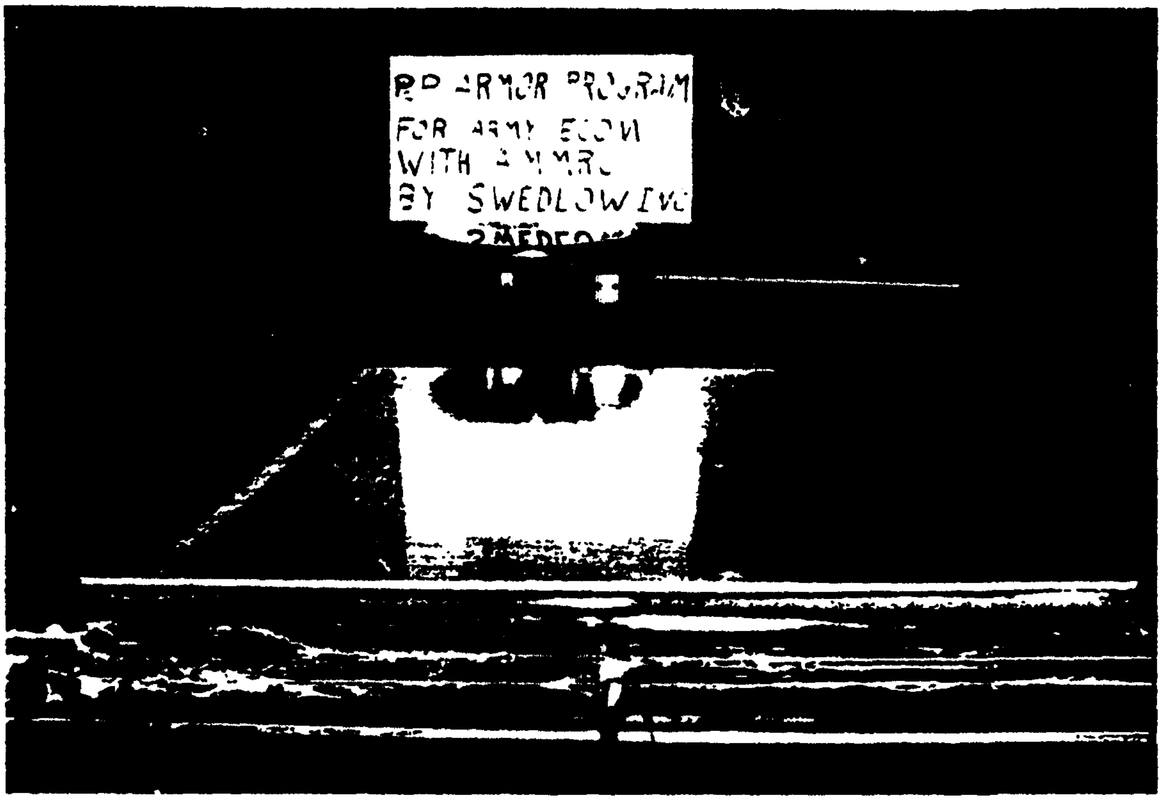
The following series of photographs depict the tooling and equipment used in PP armor production. These are arranged in normal production sequence to provide an overview of the production process.



PP film pads being sheared on the Dexter paper shear. Each pad is sandwiched between poster board to facilitate handling the cross-plied material after the hot-wire cut fused edges are removed from each pad.



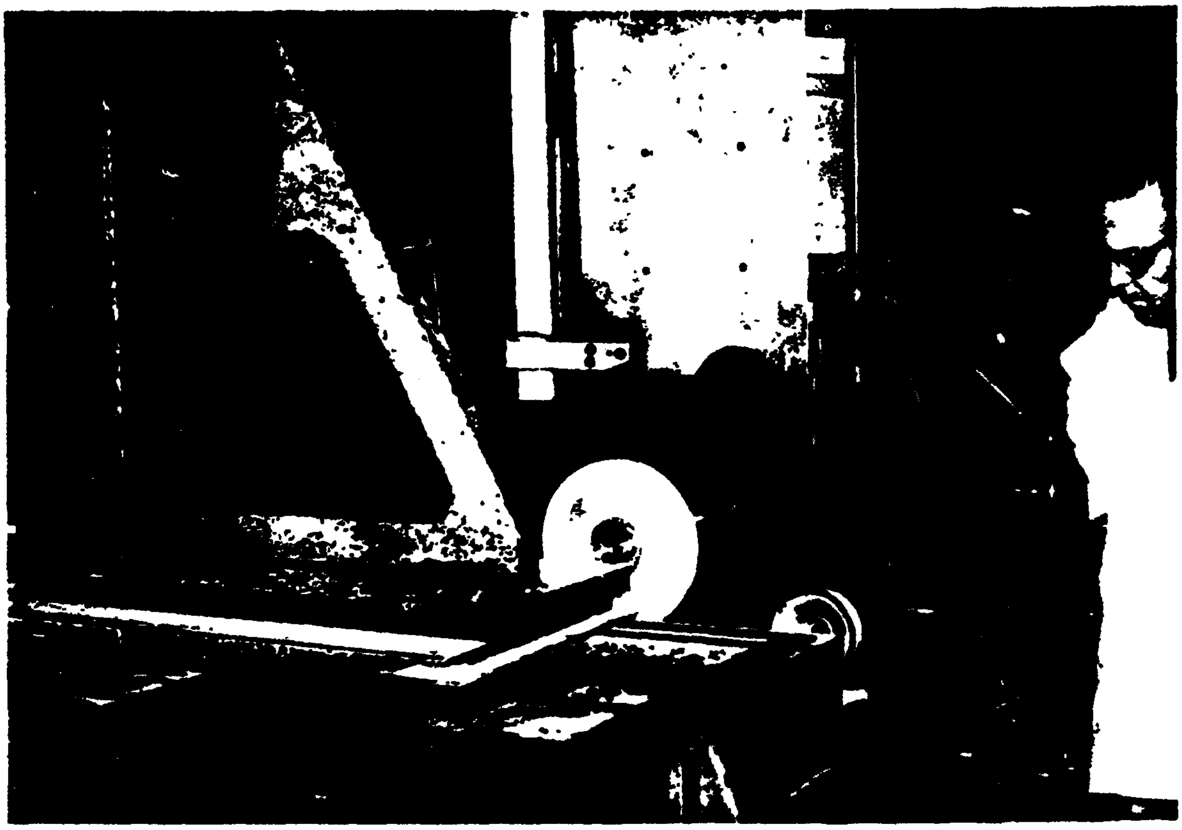
Layup assembly being weighed on 20 kilo balance. The dark cover ply on top of the PP film plies is the I89 polypropylene surface fabric. In the foreground is the bottom half of the caul plate assembly. The highly polished mold surface shows up rather dramtically in this picture.



The layup is positioned in the Caul Plate/Gasket Seal assembly. The plates are clamped together to seal the gasket, then a vacuum is applied. The clamps can then be removed during the oven drying/ evacuation cycle.

The 2000 ton Taccone press. This hydraulic press has steam/heated/water cooled platens with additional hookups for attaching dual function steam/water lines to installed molds. Steam pressure is regulated by pnuematic control valves. An air operated pump can be used to maintain maximum hydraulic pressure during long press cycles.

The evacuated assembly is installed in the mold which is mounted in the 2000 ton Taccone press. Vacuum is maintained on the layup from the oven drying cycle through the fusion cycle. 2000 psi is applied to the layup through the fusion and cooling phases of the pressing cycle. The Mold Support I-beam structure can be seen in the foreground. The thermocouple wires used for monitoring the panel midpoint and platen surface temperature can be seen taped to the vacuum line.



The molded PP armor panel has been rough trimmed on a band saw and is being machined to final dimensions on the milling machine. The rigid acrylic surface sheets which are clamped over the panel surface can be clearly seen. These sheets support the armor panel during machining and prevent edge delamination.

PRODUCT QUALITY

The product quality of the Confirmatory Sample run was subjected to various inspections and non-destructive tests per the contract requirements. A complete compilation of the requirements, along with the mechanical test data, are tabulated in a separate Quality Control Report in Appendix A of this document. The S-band frequency characteristics test data is included in a separate CONFIDENTIAL supplement to this report. A review of the requirements and a brief analysis of the results is presented here.

The V_{50} ballistic limit requirements were established per AMMRC-PD-105, 3.2.1.1 Supplement 1. The testing is to be conducted by AMMRC.

The Confirmatory Samples were tested for Radar Frequency Characteristics per AMMRC PD-105, 3.2.1.2.1 Supplement 2 by E.M.P. Inc. of Chatsworth, California. The insertion loss and boresight shift characteristics were well within the specification requirements at the specified frequencies. Test of Swedlow, Inc. PP armor panels 1.160 inches thick were conducted at Hughes Aircraft Company under Contract DAAB07-76-C-0893. Report dated September 11, 1979 verified a Dielectric Constant of 2.2 to 2.3 and ascertained the loss factor to below 0.004 but could not obtain a specific value with the method and equipment used. (Others have determined a value in the order of 0.0005.)

The dimensional tolerances specified for the armor panels required plus or minus .032 inch on the length and width and plus or minus .015 on the thickness. The deviation range for panel thickness shows the Confirmatory Panels exceeded the maximum allowable by as much as .040 inches. (Panel SN 051580.) Thus, with the process and equipment as defined, the best thickness tolerances which were obtained, exceeded the desired $\pm$ .015 inch allowable by as much as .040 inches. The maximum thickness variation within each panel, however, was considerably better, and is discussed more fully in the Problems Encountered section of this report. The machined panel length and width dimensions were not all within the specified tolerance limits, however, this problem is not related to the processing technology developed under this program. The need for such tight requirements on length and width dimensions for these panels is questionable.

During final machining and subsequent edge fusion, the heat developed can cause the panel edge to raise and initiate delamination of panel surface plies. A maximum allowable raised lip of .030 inches was established. The requirement also limited surface delamination eminating from the edge to a maximum of .060 inches. Four of the Confirmatory Panels exhibited surface ply delamination penetrating 1/4 inch along 40% of the panel edge length. It should be noted that the I89 surface plies, which contributed to the successful development of a viable molding process, are the elements which delaminate. The thick surface ply is stiff enough to bridge and overcome the poor interply bond strength of the panel film plies. The additional heat sealing steps, as described in the Heat Sealing Section of the Manufacturing Outline, can be used to lower the raised lip and re-fuse the debonded areas. The importance of edge clamping during the final machining or sawing operation cannot be over emphasized. This simple procedure can prevent localized stress release of the surface plies during machining and significantly reduce the occurrence of raised lips along the panel edges.

The panel soundness criteria requires the armor to be free of edge splits and voids, and unbonded areas and/or blisters. The Confirmatory Samples exhibited excellent edge integrity with no splits or voids noted on any of the panels. The panel surfaces also exhibited excellent integrity with no delamination or blisters noted beyond the edge surface defects previously noted.

A dimensional stability test was established with the panels cycled from -70°F to 185°F at up to 95 percent relative humidity. The quality requirements allowed minor dimensional changes and warpage increases with no allowance for edge splitting or delamination. Panels were to be examined visually for any appearance changes. The Confirmatory Samples, demonstrated excellent dimensional stability after exposure to the required thermal cycles. No appearance changes were noted, and the dimensional changes were well within the acceptable limits.

PROBLEMS ENCOUNTERED

While developing the final process for manufacturing polypropylene armor, a number of problems were encountered and resolved. These problems were not anticipated based on the work done prior to this project and; as such, required adjustments to original plans and schedules. These problems are described in the following paragraphs and their origins and solutions explained in the light of the previously described process theory.

The problems encountered can be grouped into the following types:

- o Non-bonding or delamination of plies
- o Visual defects
  - Milky appearance
  - Whitening
  - Striations
  - Opaqueness
- o Thickness control
- o Warpage

Visual defects are not described in quantitative, independent terms which creates some difficulty in describing the problem. Additionally, the effect on panel function due to these defects has not been addressed to date.

Non-bonding or delamination of plies, usually surface plies, was the most severe problem encountered and proved to be the most difficult to resolve. When this condition prevailed the remaining problems were masked by its magnitude. A number of potential causes for non-bonding exist and, thus, a lengthy experimental process was required to sort through the variables. Causes might include,

- o Inadequate fusion temperature/pressure/time
- o Surface contamination of plies
- o Mold surface contamirate permeation
- o Shear stresses induced by
  - \- pressure differentials
  - \- cool down

Variations of the process cycle resulted in examination of the following ranges of variables:

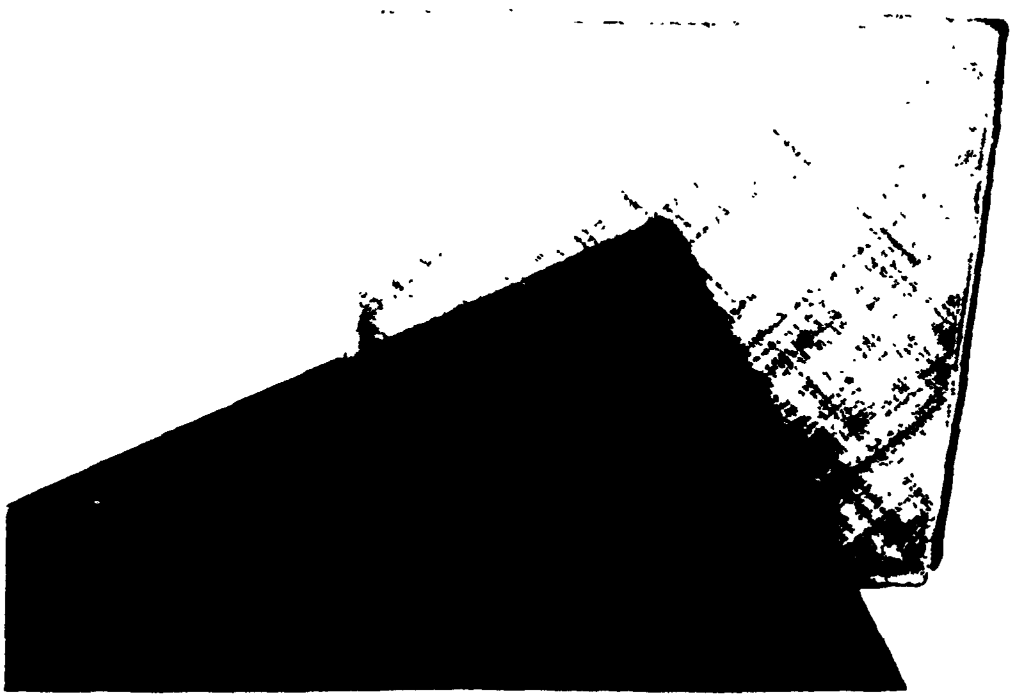
$$1900 \text{ psi} < P < 2250 \text{ psi} \qquad 45 \text{ Min} < t_f < 3 \text{ Hrs.}$$

$$40 \text{ Min} < t_r < 80 \text{ Min} \qquad 20°F < \Delta T_f \text{ (max)} < 150°F$$

$$5 \text{ Min} < t_d < 30 \text{ Min} \qquad 348°F < T_{max} < 355°F$$

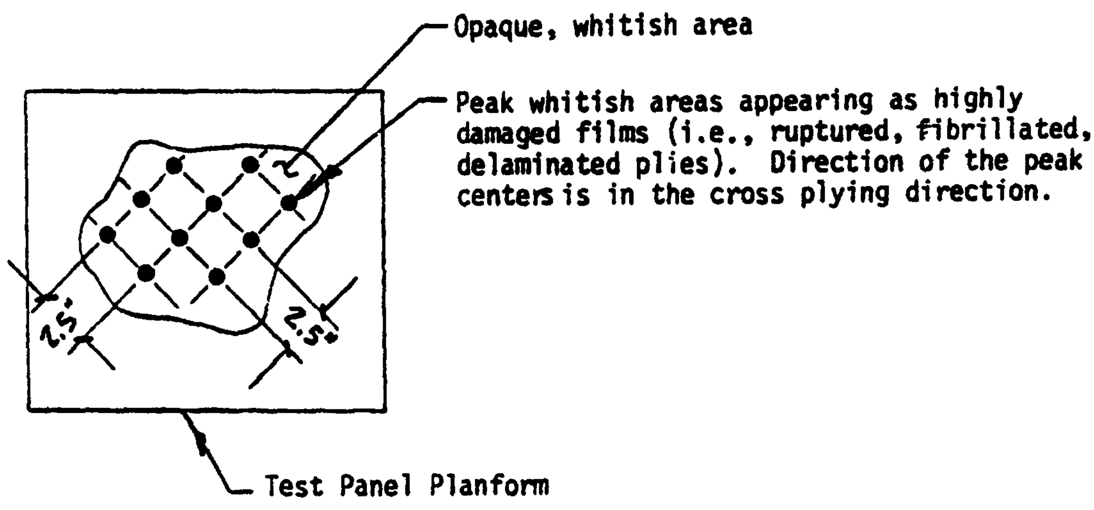
Also, various preconditionings of the film stack were tried, prior to the application of heat and pressure, to reduce contaminates. Pre-drying of the film using low heat with and without vacuum was tried, among other things, to remove any absorbed water. This sort of experimentation yielded negligible results.

Non-bonding or delamination of plies persisted until an experiment using a rubber surface sheet between the film stack and the rigid caul plate was tried. Using this .032 inch thick sheet resulted in a well bonded sheet which had excellent appearance (i.e., no whitening, striation or milky appearance). Shown below is a panel molded against 1/32" silicone rubber pads. The photo below shows the remarkable clarity obtained on the test panel.



The success of the rubber sheet pressure pad in overcoming the delamination or non-bonding problem may be explained by the pressure distribution model wherein flow is highly restricted in the central region of the panel planform coupled with the film stacks thickness variation. High local stress areas occur; first, in the central region of the panel, consistent with the described flow theory and, second, are seemingly pronounced in high thickness build-up areas created by the film cross-plying overlaps. These localized stresses cause one of two things to occur; either a tendency for shear flow is induced by the planform pressure gradients or, inadequate pressure is applied to the low points. Both of these conditions can result in a non-bonding or delaminated between film plies. The rubber pressure pad allows a more nearly hydrostatic pressure application to the film stack and, thus, overcomes the material flow and thickness variation effects.

The cross-plying of films can result in a ply overlapping condition which can yield a symmetrically patterned thickness variation to a film stack. Such a situation was found in the mandrel wound material used in this project and when subjected to fusion bonding trials using metal pressure plates, a whitish opaque pattern resulted. The typical cross hatched pattern observed on the sample panels is shown below:



This pitch of damage peaks is consistent with the film width and cross-plying overlaps dimensions. This condition is eliminated when using a rubber sheet type pressure plate.

The rubber sheet pressure pad, as noted, is more generally described (functionally) as a hydrostatic pressure pad. The final process derived from this project achieves this effect by means of the protective plies of polypropylene applied to the film stack surfaces. This material is a woven fabric about .012 inches thick and two plies of this fabric are placed adjacent to each surface during the fusion bonding cycle. Melting occurs more readily in this material and it acts to redistribute pressures, thus simulating the hydrostatic pressure pad effect. The surface protection pad is therefore multi-functional as it provides the means to obtain a well bonded laminate and at the same time becomes integral with the armor and protects the substrate from environmental effects.

Another significant development was the introduction of a mirror finish on the caul plates. This was essential in avoiding panel surface delamination or non-bonding. The normal finish is not adequate in permitting panel surface movement and avoiding internal stress during cool down.

Optimization of the processing parameters resulted in a reduction or elimination of the defects noted. Panels were molded with little or no visual defects, delaminations, and warpage. Panel thickness variations persisted, however, throughout the program. This problem occurred as thickness variations within each panel, with the center always thicker, and as variations of average thickness from panel to panel.

The restricted flow in the central area of the panel, which was previously discussed, contributes to the significant thickness variation within each panel. This was demonstrated by molding two half sized panels side by side and comparing the thickness variations of each to a full sized panel. In each case the central area was up to .050 inches thicker than the corners. This thickness variation of 0.050 inches within a panel represents a tolerance range of $\pm$ .025 inches, which is not unreasonable for large area flat panels. This tolerance range, however, when added to the thickness variation from panel to panel, resulted in an unacceptable thickness range.

To minimize the variations in average thickness from panel to panel, the processing cycle parameters were revised. Previous cycle control was based on attainment of a 348°F to 350°F mid-point temperature. This resulted in unacceptable variations in cycle times and therefore unpredictable material flow. The final selected cycle established a time-at-platen-temperature requirement for each thickness. This cycle standardization provided more predictable flow from panel to panel, and resulted in better replication of average panel thickness.

MANUFACTURING CAPABILITY

The manufacture of PP armor panels, by the processing technology developed under this program, will require capital equipment and tooling as previously described. An engineering analysis of the production rate capability of Swedlow, Inc., based on the equipment on hand, is presented. This analysis is based on the availability of cross-plied oriented polypropylene film pads from an approved source, and converting the 2000 ton Taccone press to a multiple platen operation with five cavities.

The controlling factor for production rate capability will be a function of the press tonnage and platen area size versus the molding pressure required. In this case with 2000 ton available press capacity, the maximum panel size which can be molded at 2000 psi is a sheet 44 inches square. After trim, the useable area is about 12 square feet. Molding five panels at a time will yield 60 square feet per press cycle.

The maximum production capability based on a three shift per day-five day week, will be 1200 square feet of one inch thick PP armor per week. This is based on a six hour cycle for the one inch thickness. The three-eighths thickness armor panels require a three hour cycle and can therefore be produced at 2400 square feet per week.

A preliminary analysis of direct labor requirements indicates finished panels at 44 inches square can be molded with a labor content of about one-half man hour per square foot. Three-eighth inch thick panels will require approximately three-tenths of a man hour per square foot.

To achieve this production capacity will require a capital expenditure of approximately 50,000 dollars to convert the Taccone press to a multiple platen mode. Additional Caul Plate Assemblies and Gasket Seals will cost an additional 40,000 dollars. Thus, for under 100,000 dollars an annual production capacity of from 60 to 120 thousand square feet per year can be realized. This will require a film production rate of from one hundred thousand to three hundred thousand pounds of material per year.

The requirement for a reliable source of high draw ratio oriented polypropylene film could be a serious problem in achieving a viable production capability of PP armor. The only producer of acceptable film at this time is AMMRC. The AMMRC facility converts blown film to the high draw ratio product on equipment with a maximum capacity of approximately 200 pounds per shift. Even a three shift operation will only yield one half the annual requirement of the projected Swedlow, Inc., capacity. An intermediate film source with a capacity of from 150,000 to 1,000,000 pounds of oriented film per year must be obtained to achieve a reliable PP armor production capability.

RECOMMENDATIONS

The following recommendations are offered as a logical extension of this program effort to improve the establishment of PP Armor fabrication on a commercial basis.

- Develop approved sources for high draw ratio oriented polypropylene film.

  Presently, the only source for uniaxially oriented polypropylene film suitable for producing PP Armor is AMMRC. A commercial processor of suitable film is essential for high volume production capacity. Swedlow, Inc. has in storage government owned equipment that if rehabilitated and supplemented by unwind and rewind stands, would be capable of producing satisfactory high draw ratio film.

- Evaluate methods of obtaining the required thickness control by secondary operations.

  A possible method of achieving positive thickness control would be to apply a layer of un-oriented polypropylene to previously molded PP Armor panels. This assembly can be molded against positive stops at a temperature below the melting point of the oriented film plies. This will allow the facing material to flow until the stop pads are fully engaged. The resulting composite structure will have predictable flatness and thickness. Methods to achieve a suitable bond between the armor panel and facing materials will require investigation.

- Order pilot run quantities of PP armor panels.

  As previously noted, the pilot run quantities were deleted from this program due to technical difficulties encountered during the initial program efforts. This additional effort required the use of funds allocated for the pilot run. The purpose for the pilot run was to validate the production process and verify replication of panel quality through a production lot of 64 panels. Production of a pilot run quantity would provide additional confirmation of the manufacturing methods and technology developed under this program. The panels produced could also be used to fabricate radar array systems for field testing which would allow in-service problem identification.

- Consider heat transfer fluid system to replace steam heating.

  Although steam heating and water cooling was used throughout this program, it is recommended that a heat transfer fluid system be considered for full scale production of PP armor panels. The main problem encountered with steam heating is the difficulty in achieving precise temperature control. Even with pneumatic steam pressure control valves, it is extremely difficult to hold the platen surfaces to within ± 3 degrees F of the target temperature. The closer temperature control which can be achieved with a liquid heat transfer medium will produce more predictable plastic flow during the fusion operation and result in better replication of panel-to-panel thickness.

- Alternate bonding techniques.

  The fusion bonding techniques, developed under this program, require high pressures and precise temperature control to produce PP armor panels. The precise temperature control is necessary to limit the melt fraction to the minimum amount necessary for bonding the film plies. Any excess melt fraction will cause a corresponding decrease in ballistic performance. The high pressure is required to prevent orientation stress release of the film plies at the required fusion temperature. It follows, then, that a bonding media applied to the oriented film, could allow fusion at lower temperature and pressure, provided it had a lower melting point than the oriented film plies. The coating material would have to match the electrical characteristics of polypropylene, and constitute less than 2 percent of the material weight, to provide comparable ballistic and radar transmission properties. This ability to mold at a lower temperature and pressure could provide a substantial increase in production capacity through larger area panels and reduced cycle times. A program to evaluate this and other alternate bonding techniques should be considered.

CONCLUSIONS

The objectives of this program have been successfully accomplished. Manufacturing technology has been established for the production of PP armor panels for radar antenna hardening. The production of the Confirmatory Samples demonstrated the validity of production rate estimates of up to 120,000 square feet per year. This rate should be sufficient for prototype systems development and evaluation, and provide a sound technical base for establishing high volume production facilities for the oriented film and PP armor panels.

As a direct result of the manufacturing and methods technology advancements of this program, Swedlow, Inc. produced some four inch thick spherical segments of PP armor for the Naval Research Laboratory. These panels validated the feasibility of process scale up to fusion bond thick, curved PP armor to provide increased threat ballistic protection.

Thus, a range of shapes and thicknesses are now producible in polypropylene armor allowing protection of various devices from a range of ballistic threats.

APPENDIX A

QUALITY CONTROL REPORT

CONFIRMATORY SAMPLES

CONTRACT DAAB07-77-C-0476

1. Requirements
2. Electrical Tests
3. Dimensional Tolerances
4. Edge Finish & Soundness
5. Dimensional Stability

CONFIRMATORY SAMPLES

PRODUCT INSPECTION REPORT

REQUIREMENTS

Inspect in accordance with Table 4.1.2 of MIL-STD-105

Requirement	Test Procedure	Responsibility
ballistic (3.2.1.1 and Supplement 1)	4.2.4	AMMRC(1)
S-band frequency characteristics (3.2.1.2 and Supplement 2)	Supplement 2 and 4.2.8	Swedlow, Inc.(2)
Sizes and tolerances (3.2.2.1)	Standard	Swedlow, Inc.
Camouflage (3.2.2.2)	MIL-E-52798 and standard	Not Applicable(3)
Edge finish (3.2.2.3)	Standard	Swedlow, Inc.
Dimensional Stability (3.2.2.4)	4.2.5	Swedlow, Inc.
Soundness (3.2.2.5)	Standard	Swedlow, Inc.

(1) Per P.47 Paragraph C.

"C. All testing will be conducted by the successful offeror except for Ballistic Tests which will be conducted by the Army Materials and Mechanics Research Center."

(2) S-band frequency characteristics were conducted per (3.2.1.2 - Supplement 2), by Electro-Magnetic Processes Inc., of Chatsworth, California. This report, identified as R-630 by EMP, is included as a classified supplement to this document.

(3) Revised contract required Confirmatory Panels to be Style 1 only. Camouflage requirement is for Style 2 panels.

CONFIRMATORY SAMPLES

PRODUCT INSPECTION REPORT

DIMENSIONAL TOLERANCES

3.2.2 Physical characteristics.

3.2.2.1 Sizes and tolerances. Cut and fused edge panels (Finish 2) shall be 24 x 34 inches within a tolerance of plus or minus 0.032 inch. Dimensional tolerances for lengths and widths of molded edge panels (Finish 1) in Size 1 and 2 shall be plus or minus 0.07 inch. Thickness tolerances for all panels shall be plus or minus 0.015 inch.

QUALITY CONTROL INSPECTION RECAP

	Thickness		Length		Width		Maximum
Panel S/N	Range	Deviation	Range	Deviation	Range	Deviation	Warpage
013080	1.163	-0-	33.925	- .043	23.959	- .009	.011
	1.203	+ .028	33.996	-0-	24.036	+ .004	
051580	1.173	-0-	33.939	- .029	23.934	- .034	.011
	1.215	+ .040	33.980	-0-	24.030	-0-	
050980	.370	-0-	33.970	-0-	23.960	- .008	.055
	.413	+ .023	34.033	+ .001	24.025	-0-	
013180	1.134	- .011	33.975	-0-	23.970	-0-	.039
	1.180	+ .005	34.038	+ .006	24.027	-0-	
051480	1.126	- .019	33.970	-0-	23.970	-0-	.046
	1.169	-0-	34.020	-0-	24.035	+ .003	
051280	.346	- .014	33.950	- .018	23.885	- .083	.011
	.390	-0-	33.980	-0-	24.015	-0-	
051980	.370	-0-	33.955	.013	23.980	-0-	.028
	.409	+ .019	33.998	-0-	23.995	-0-	
051680	.365	-0-	33.963	- .005	23.980	-0-	.050
	.399	+ .009	34.009	-0-	24.030	-0-	

CONFIRMATORY SAMPLES

PRODUCT INSPECTION REPORT

EDGE FINISH AND SOUNDNESS

3.2.2.3.2 Cut and fused edges. The molded panels shall be cut to size and the edges finished by fusion either as part of the cutting process or as a separate operation subsequent to cutting. The finished edge shall not be split, shall not have a raised lip greater than 0.030 inch in height and shall not be delaminated as evidenced by whitish borders on the sheet faces to an extent greater than 0.060 inch from the edges.

3.2.2.5 Soundness. The armor panels shall be translucent and may show striations indicative of the mandrel winding pattern. They shall be free of edge splits and voids, unbonded areas and blisters as evidenced by whitish areas.

QUALITY CONTROL INSPECTION RECAP

Panel S/N	Raised Lip (Maximum Height)	Defects Noted
013080	.027	Surface ply delamination 1/4" over 20% of edge length. No panel delamination or edge split.
051580	.032	Surface ply delamination 3/16" over 30% of edge length. No panel delamination or edge split.
013180	.017	No delamination or edge splits.
051480	.023	No delamination or edge splits.
050980	.019	No delamination or edge splits.
051280	.024	Surface ply delamination 3/16" over 40% of edge length. No panel delamination or edge splits.
051980	.021	Surface ply delamination 1/4" over 35% of edge length. No panel delamination or edge splits.
051680	.017	No delamination or edge splits.

CONFIRMATORY SAMPLES

PRODUCT INSPECTION REPORT

DIMENSIONAL STABILITY

3.2.2.4 Dimensional stability. The armor panels shall be dimensionally stable and shall not split or delaminate when test in accordance with 4.2.5. The maximum acceptable change is 0.04 inch decrease in length and width, and 0.010 inch increase in thickness, and 0.06 inch increase in warpage.

4.2.5 Dimensional stability. Armor panels shall be measured for length and width along centerlines and for thickness at the center. Any existing warpage shall be determined by moving a straight edge longer than the diagonal of the panel over the concave side and measuring the maximum gap between the bottom of the straight edge and the panel surface. The measured panel shall be subjected to the below designated temperature and the humidity cycle in a test chamber. There shall shall be a two hour transition period between cycle phases and between room conditions and the start and conclusion of the cycle in which to change gradually the chamber conditions. The chamber shall start and end at room temperature and humidity conditions.

Cycle Phase (in order)	Duration, Hours
A	4
B	16
C	4
A	16
B	4
C	16

Phase A: 185 F and 95 percent relative humidity

Phase B: -70 F

Phase C: 185 F

Upon completion of the cycle, the panels shall be remeasured for length, width and thickness dimensions, for warpage, and shall be examined visually for edge splits and debonded areas as indicated by the appearance of whitish areas or blisters. The change in dimensions and in warpage shall be calculated.

QUALITY CONTROL INSPECTION RECAP

Panel S/N	Dimensional Change				Surface
	Length	Width	Thickness	Warpage	Appearance
120479	+ .023	+ .032	- .006	- .010	No Change
101679	- .017	- .024	+ .007	- .012	No Change
057080	- .015	- .018	+ .003	+ .050	No Change
112879	- .010	- .014	+ .009	+ .010	No Change
121879	- .021	- .027	+ .005	- .003	No Change

Army Materials and Mechanics Research Center
Watertown, Massachusetts 02172
MOLDING OF POLYPROPYLENE FILM ARMOR
FOR RADAR ANTENNA HARDENING APPLICATIONS
Glenn A. Cook
Swedlow, Inc.
12122 Western Avenue
Garden Grove, CA 92645
Technical Report AMMRC TR80-54, Jan., 1981
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Unlimited Distribution

Key Words

Armor
Laminates
Polymeric Films
Radomes

The general objective of this project was to establish a production capability for rigid armor panels molded from cross-plied, unidirectionally oriented polypropylene film. Armor of this type has applicability as radome material. The purpose of establishing this production capability is to provide for the contingency of meeting estimated military needs for a period of two years after completion of the contract and, to establish a base and plans which may be used to meet expanded requirements. These tasks were successfully performed and the general objective of this project has been achieved. A production capability for polypropylene armor has been established, and in the process, opportunities for additional process advances have been identified.

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